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Moriarty et al.

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(54) **DRILLING BOTTOM HOLE ASSEMBLY HAVING WIRELESS POWER AND DATA CONNECTION**

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(51) **Int. Cl.**

E21B 17/04	(2006.01)
E21B 17/02	(2006.01)
E21B 7/04	(2006.01)
E21B 47/12	(2012.01)
E21B 4/02	(2006.01)

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(52) **U.S. Cl.**
CPC ***E21B 17/028*** (2013.01); ***E21B 4/02*** (2013.01); ***E21B 7/04*** (2013.01); ***E21B 7/068*** (2013.01); ***E21B 47/122*** (2013.01); *E21B 41/0085* (2013.01)

(58) **Field of Classification Search**
CPC E21B 4/02; E21B 7/04; E21B 7/068; E21B 17/028; E21B 41/0085; E21B 47/01; E21B 47/02
See application file for complete search history.

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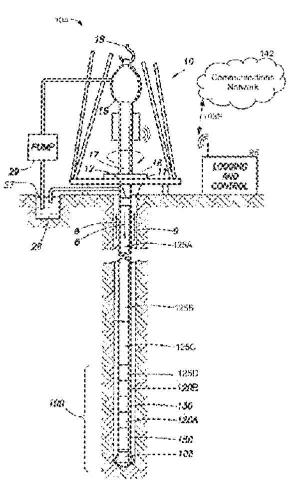
(74) *Attorney, Agent, or Firm* — John Vereb

(57) **ABSTRACT**

A bottom hole assembly (BHA) configured for use in a drill string of a wellsite drilling system. The BHA includes a measuring-while-drilling (MWD) module, a wireless power and data connection, and a rotary steerable system (RSS). The MWD module is configured for coupling to a drill string, and includes a power generation component and a direction and inclination (D&I) survey package. The wireless power and data connection is disposed above a drilling motor in the drill string and for providing power and data connectivity between the MWD module and the drilling motor. The RSS is coupled to the drilling motor for receiving power from and communicating with the MWD module via the wireless power and data connection and the drilling motor.

12 Claims, 18 Drawing Sheets



(51) **Int. Cl.**
E21B 7/06 (2006.01)
E21B 41/00 (2006.01)

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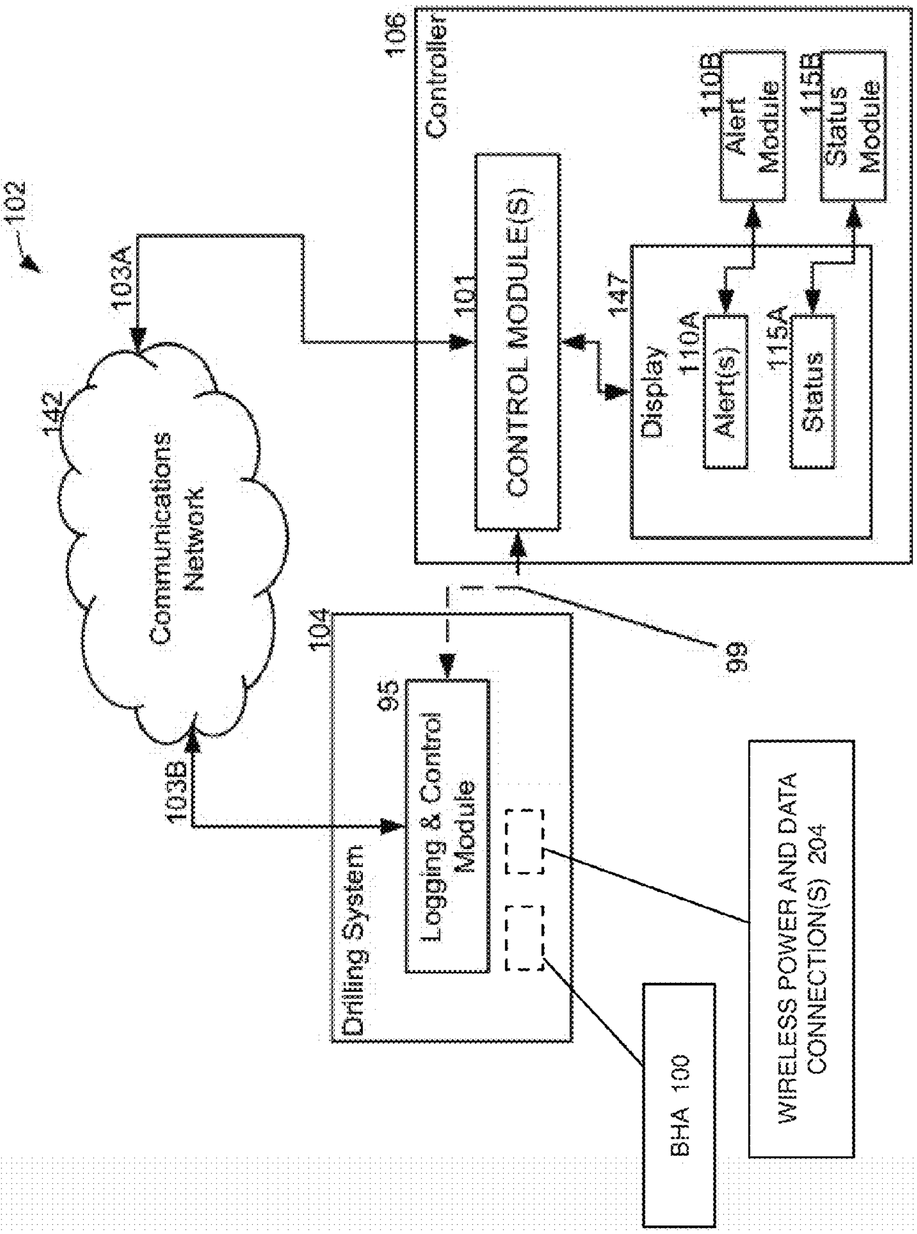
102
103A
142
Communications Network
101
CONTROL MODULE(S)
106
Controller
147
Display
110A
Alert(s)
115A
Status
110B
Alert Module
115B
Status Module
104
Drilling System
95
Logging & Control Module
103B
99
BHA 100
WIRELESS POWER AND DATA CONNECTION(S) 204

FIG. 1A

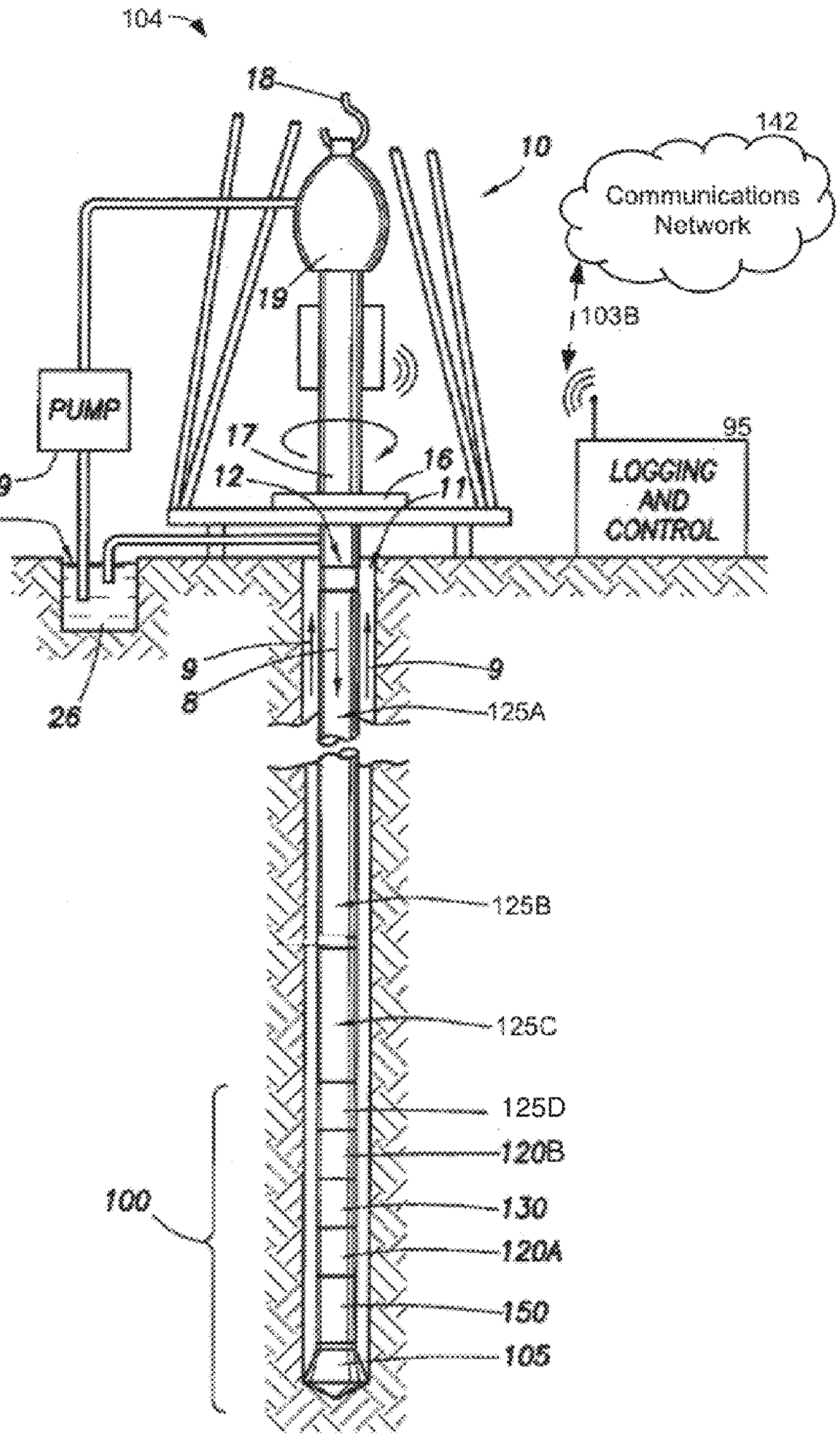
104
18
10
142
Communications Network
19
103B
PUMP
95
LOGGING AND CONTROL
17
16
12
11
29
27
9
9
8
125A
26
125B
125C
125D
120B
100
130
120A
150
105

FIG. 1B

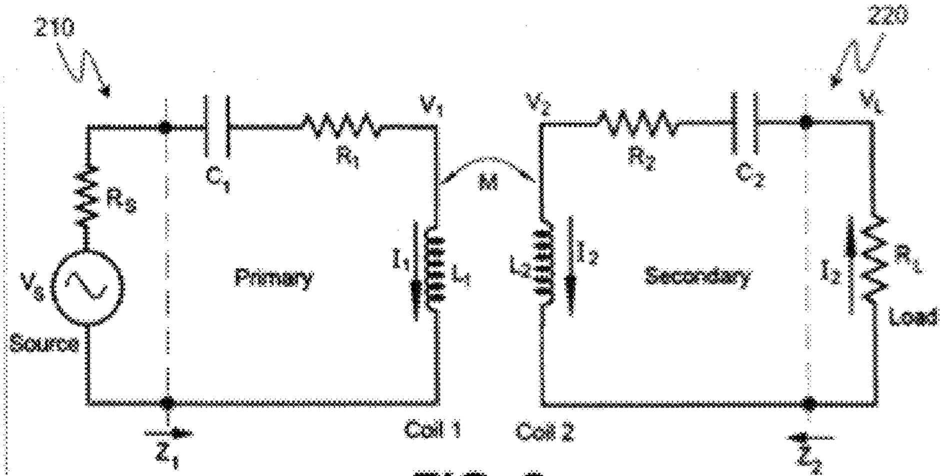

FIG. 2

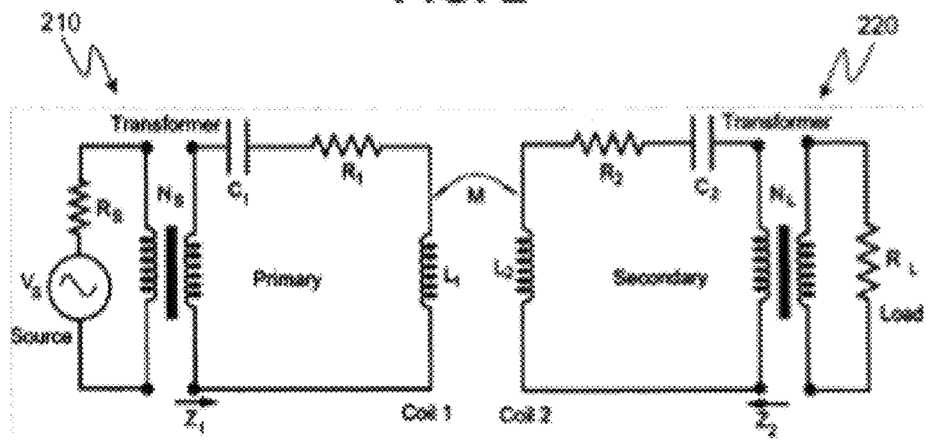

FIG. 3

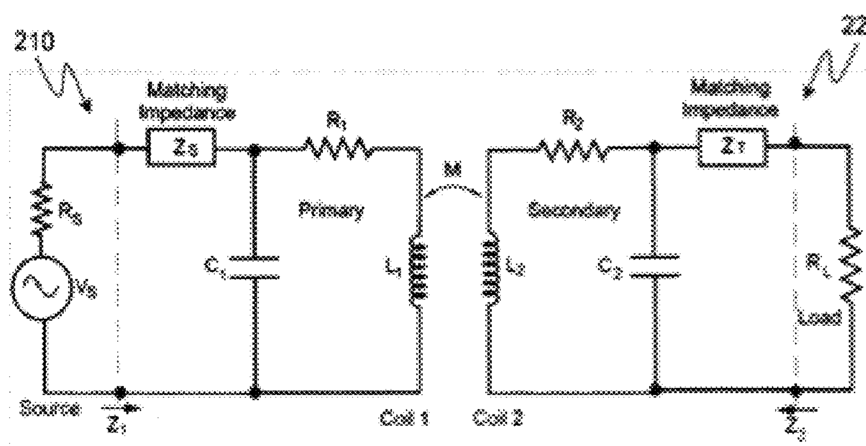

FIG. 4

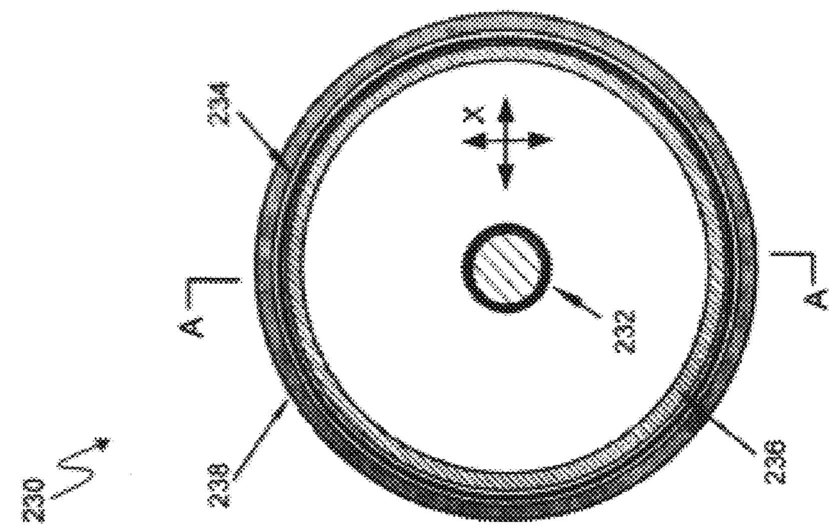
230
234
238
236
232
A
A
X

FIG. 5B

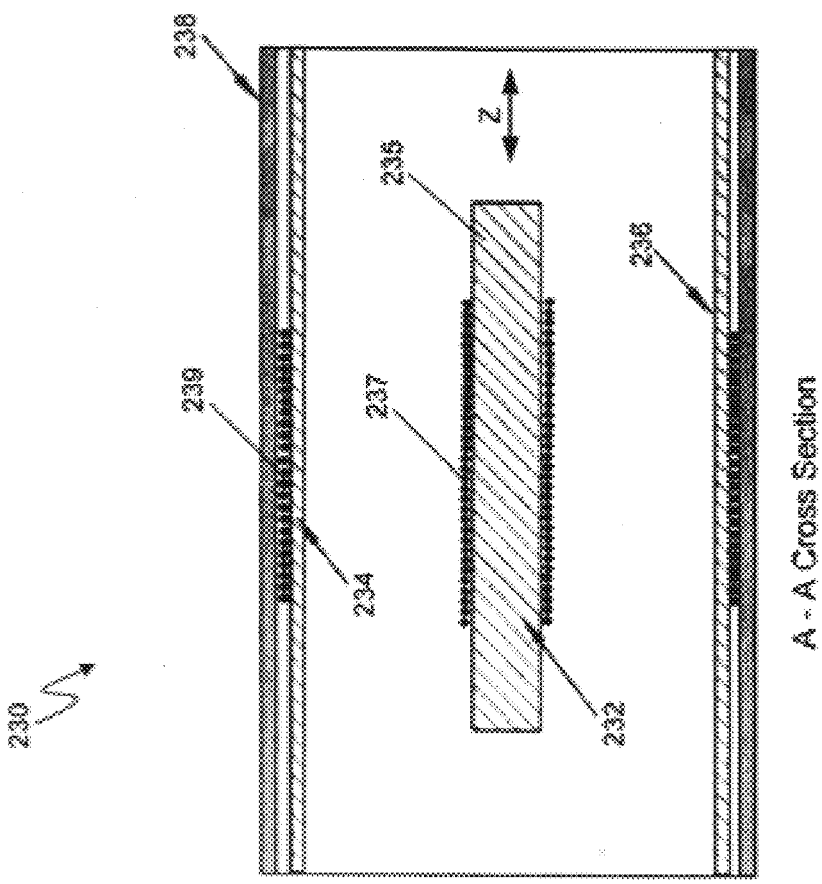
230
238
239
234
237
235
236
232
Z
A - A Cross Section

FIG. 5A

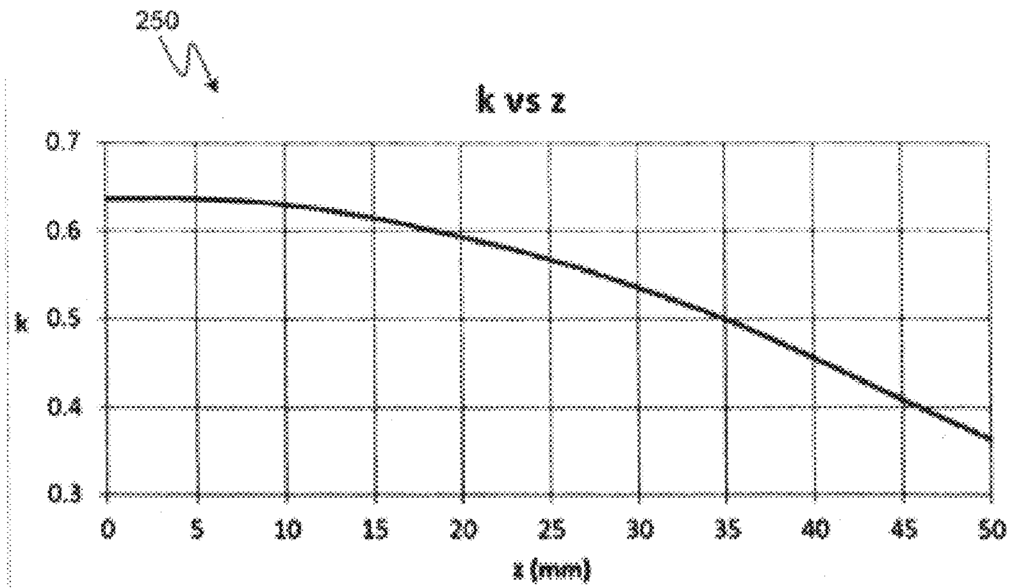
250
k vs z
k
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
35
40
45
50
x (mm)

FIG. 6

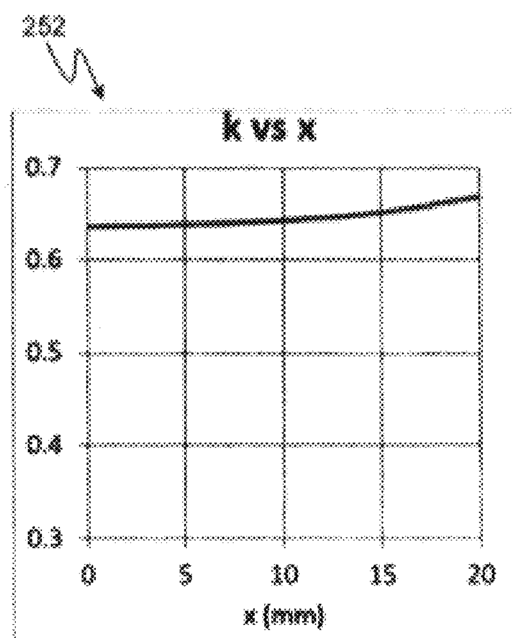
252
k vs x
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
x (mm)

FIG. 7

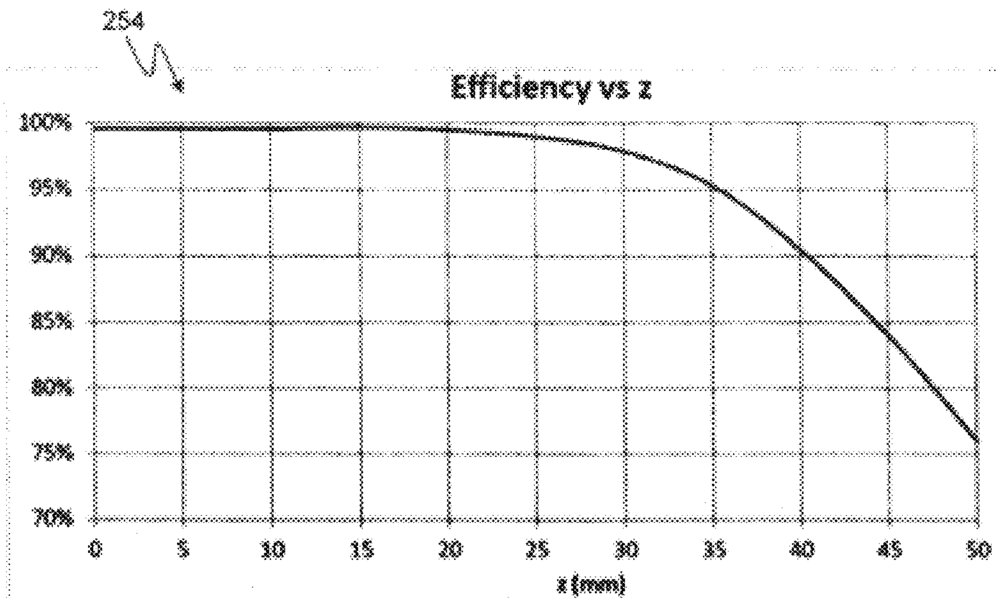
254
Efficiency vs z
100%
95%
90%
85%
80%
75%
70%
0
5
10
15
20
25
30
35
40
45
50
z (mm)

FIG. 8

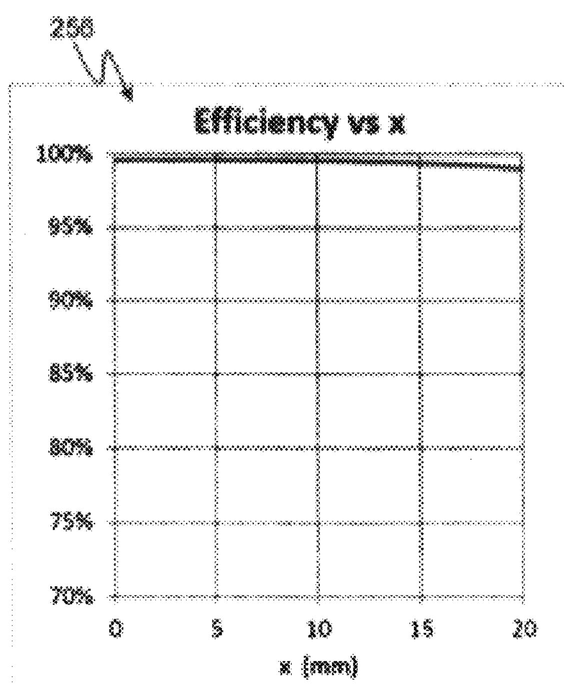
256
Efficiency vs x
100%
95%
90%
85%
80%
75%
70%
0
5
10
15
20
x (mm)

FIG. 9

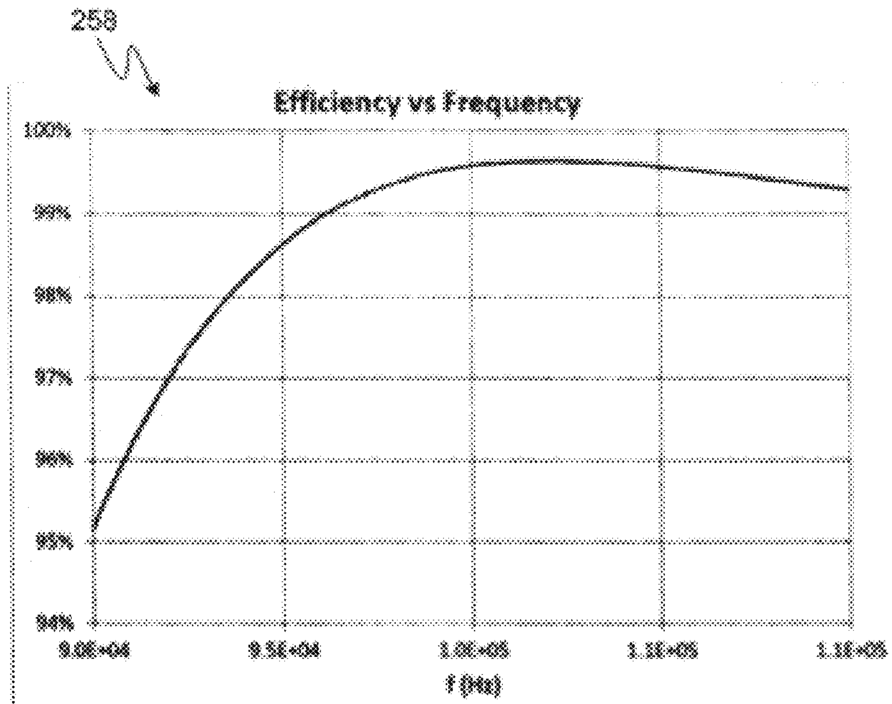
258
Efficiency vs Frequency
100%
99%
98%
97%
96%
95%
94%
9.0E+04
9.5E+04
1.0E+05
1.1E+05
1.1E+05
f (Hz)

FIG. 10

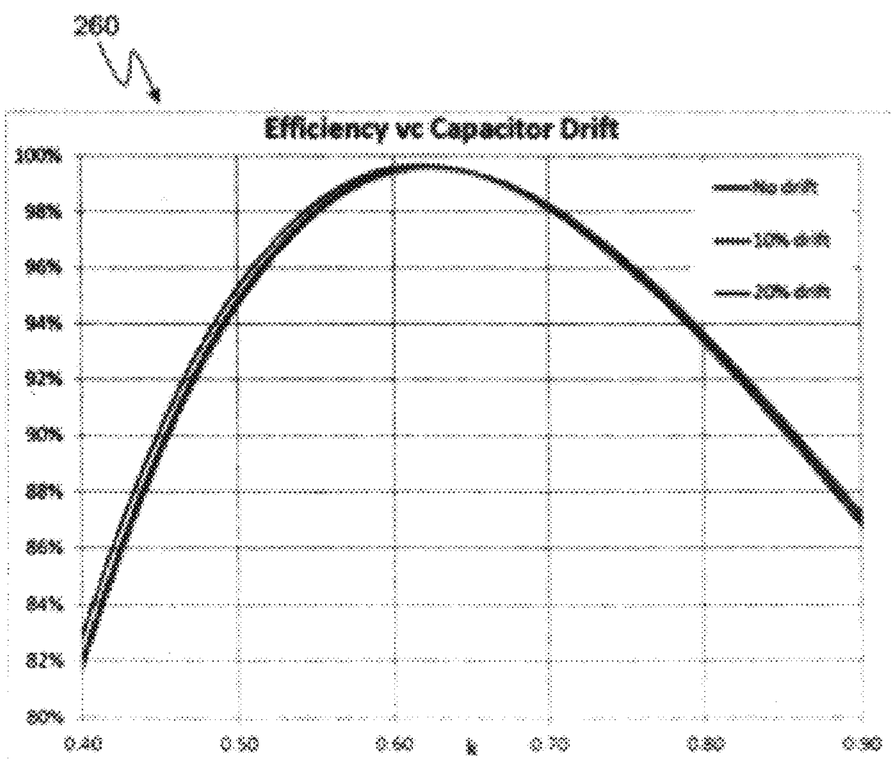
260
Efficiency vc Capacitor Drift
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
No drift
10% drift
20% drift
0.40
0.50
0.60
k
0.70
0.80
0.90

FIG. 11

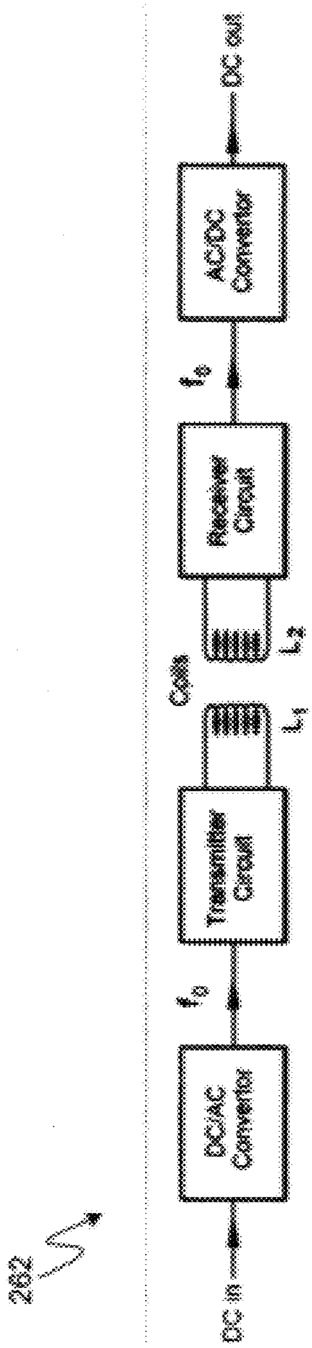
262
DC in
DC/AC Converter
f_0
Transmitter Circuit
L_1
Coils
L_2
Receiver Circuit
f_0
AC/DC Converter
DC out

FIG. 12

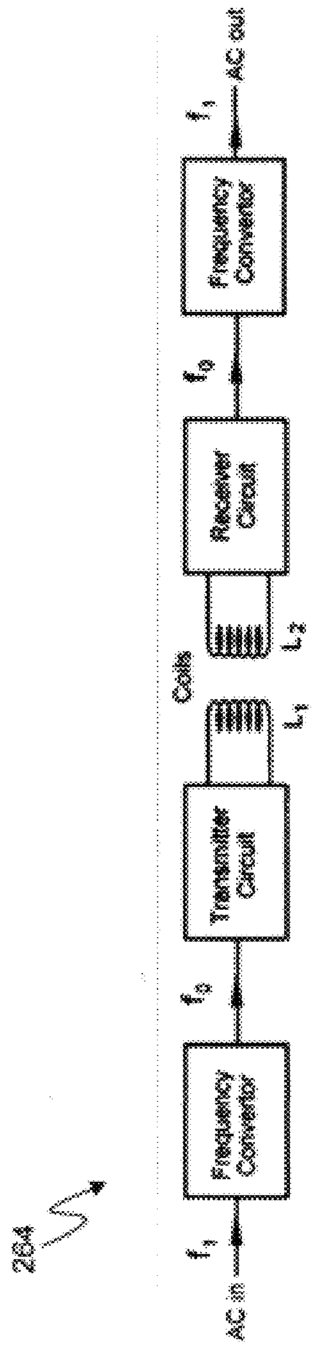
264
AC in
f_1
Frequency Converter
f_0
Transmitter Circuit
L_1
Coils
L_2
Receiver Circuit
f_0
Frequency Converter
f_1
AC out

FIG. 13

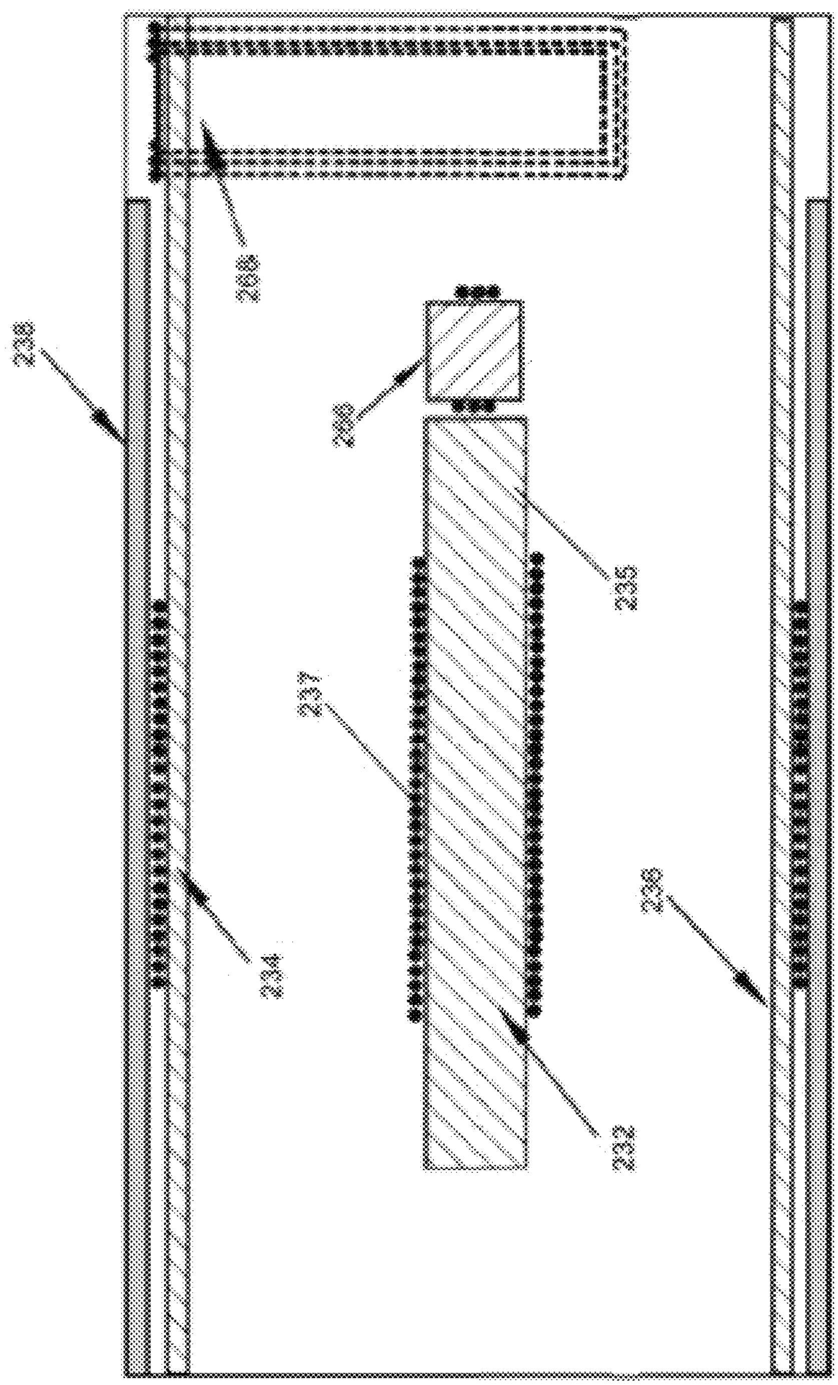

FIG. 14

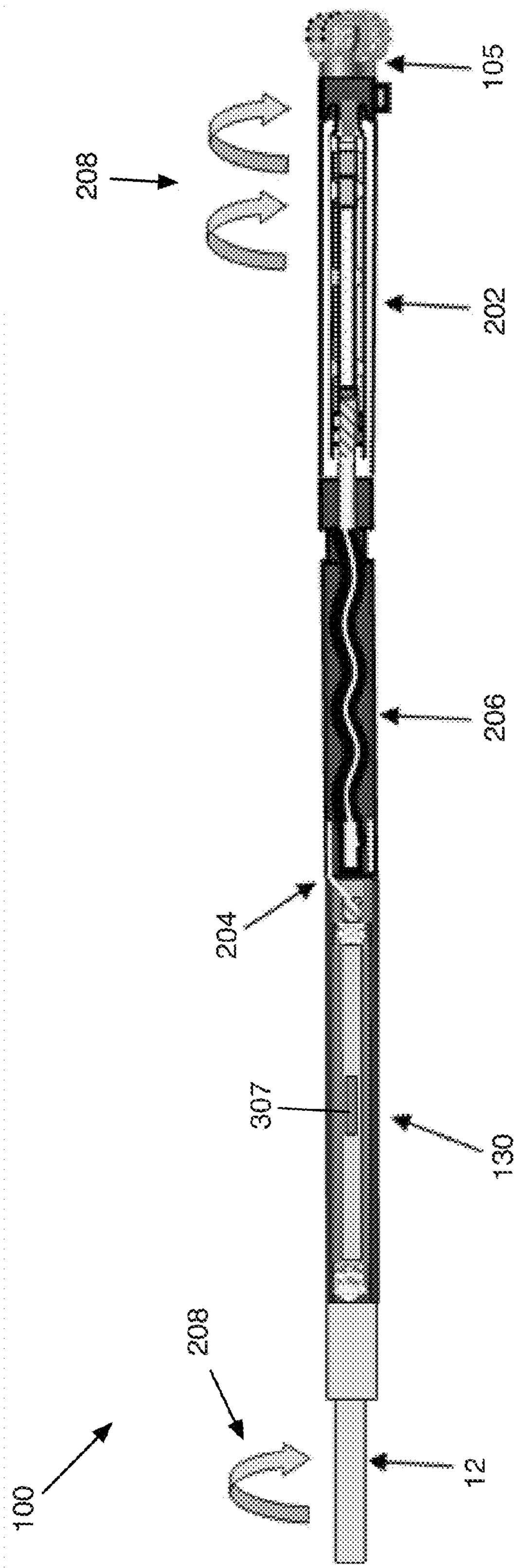

FIG. 15

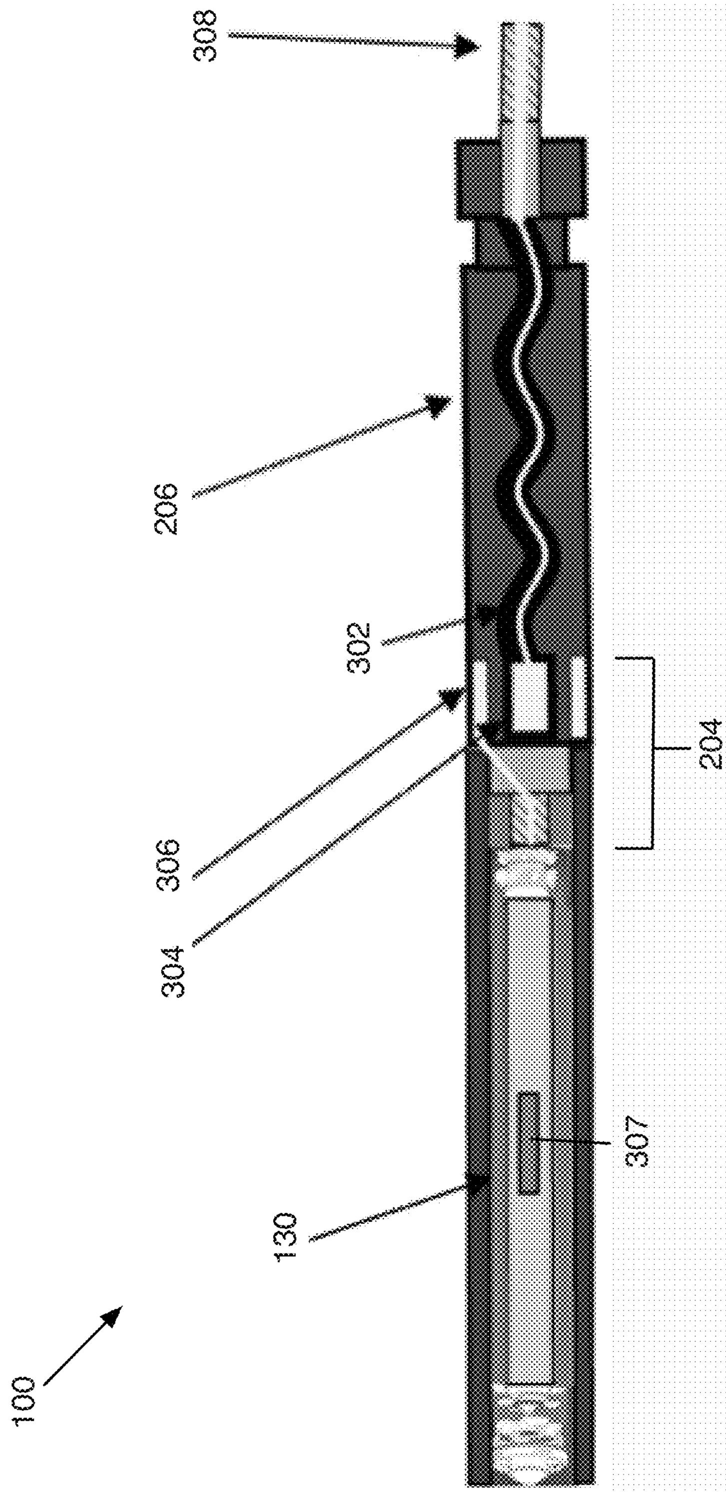

FIG. 16

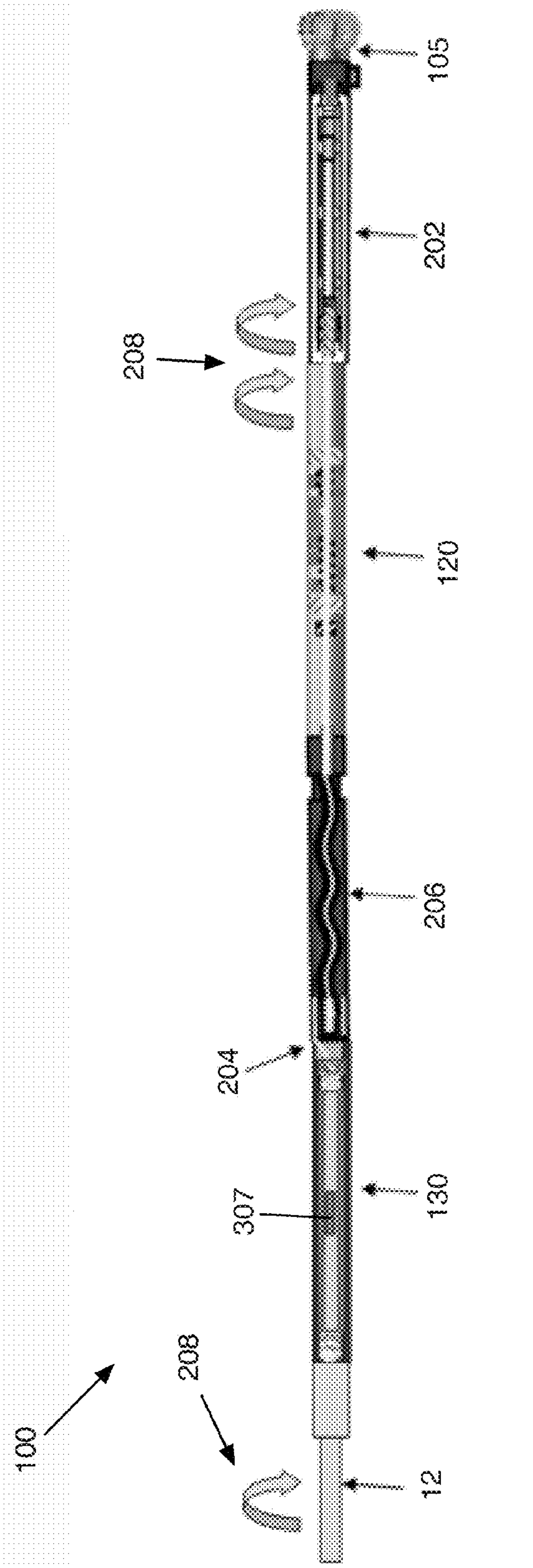

FIG. 17

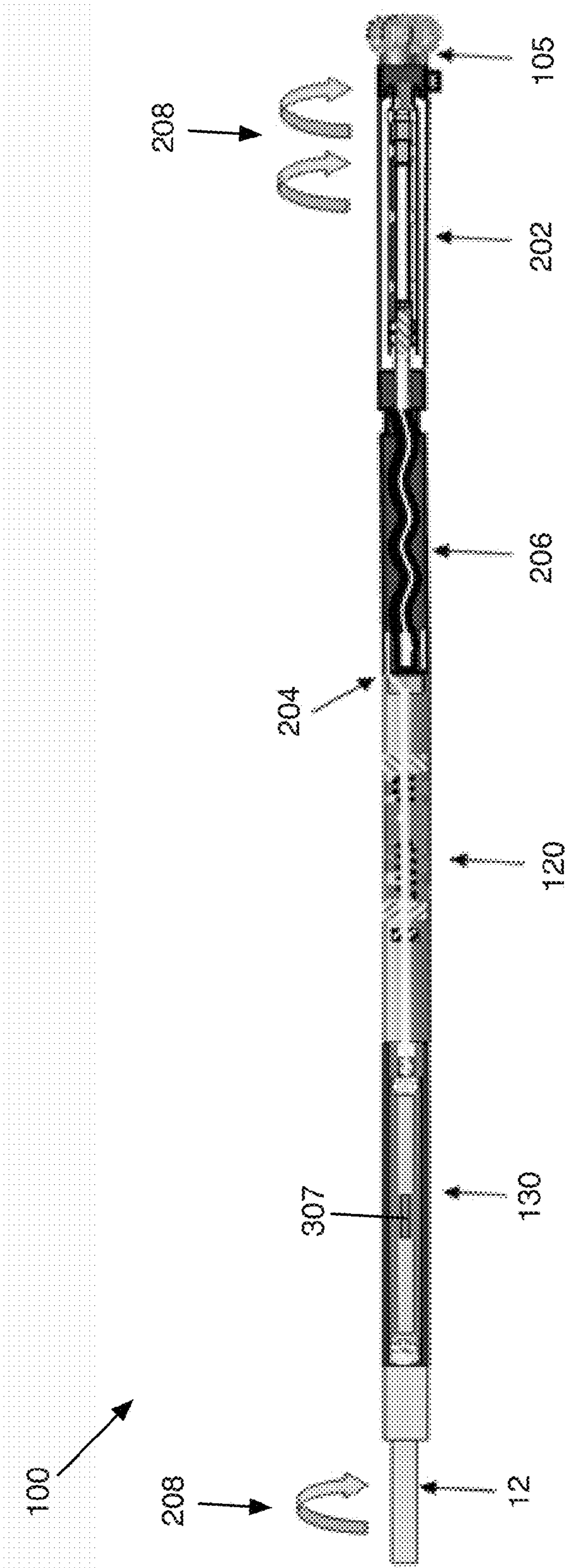

FIG. 18

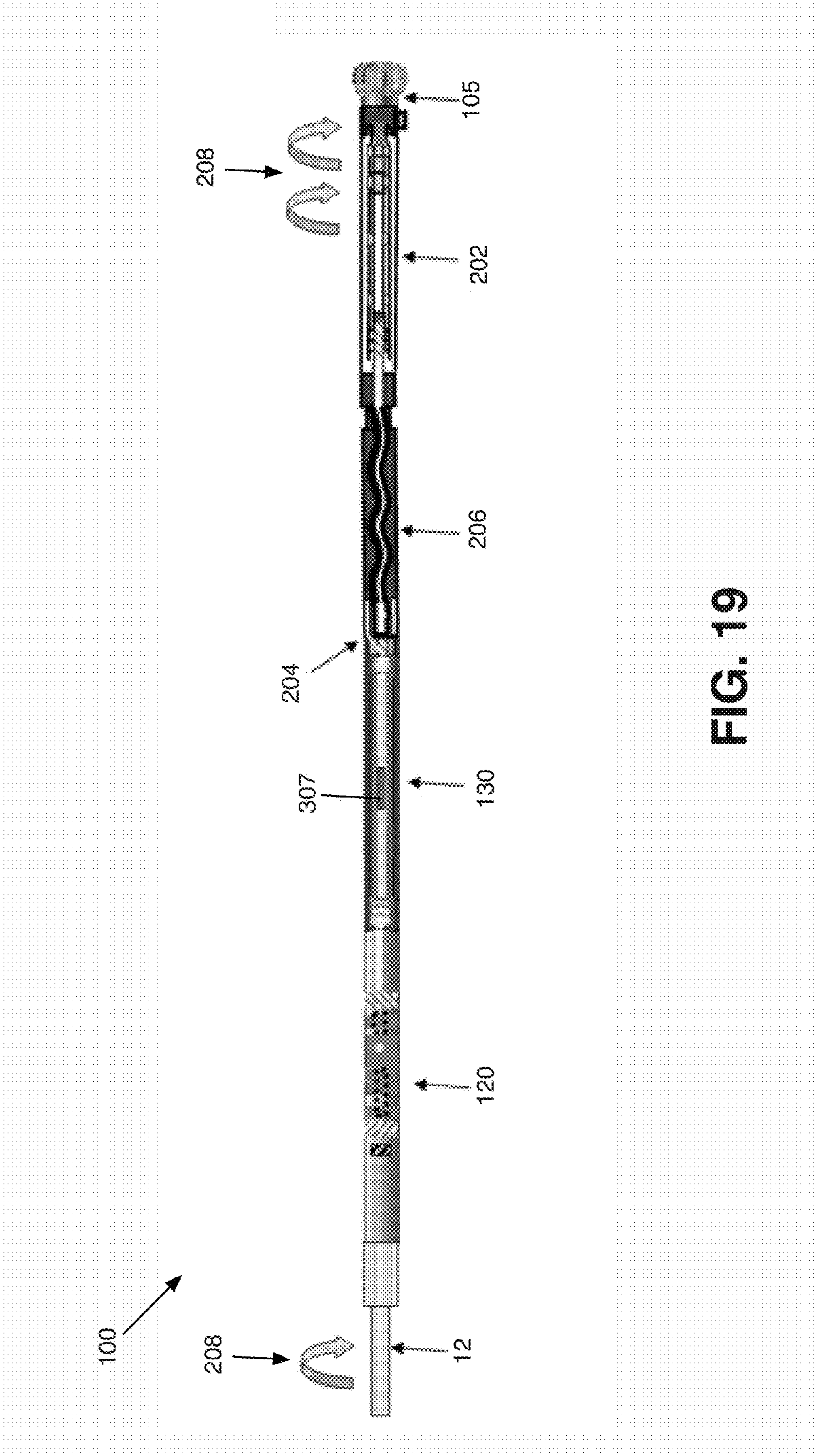

FIG. 19

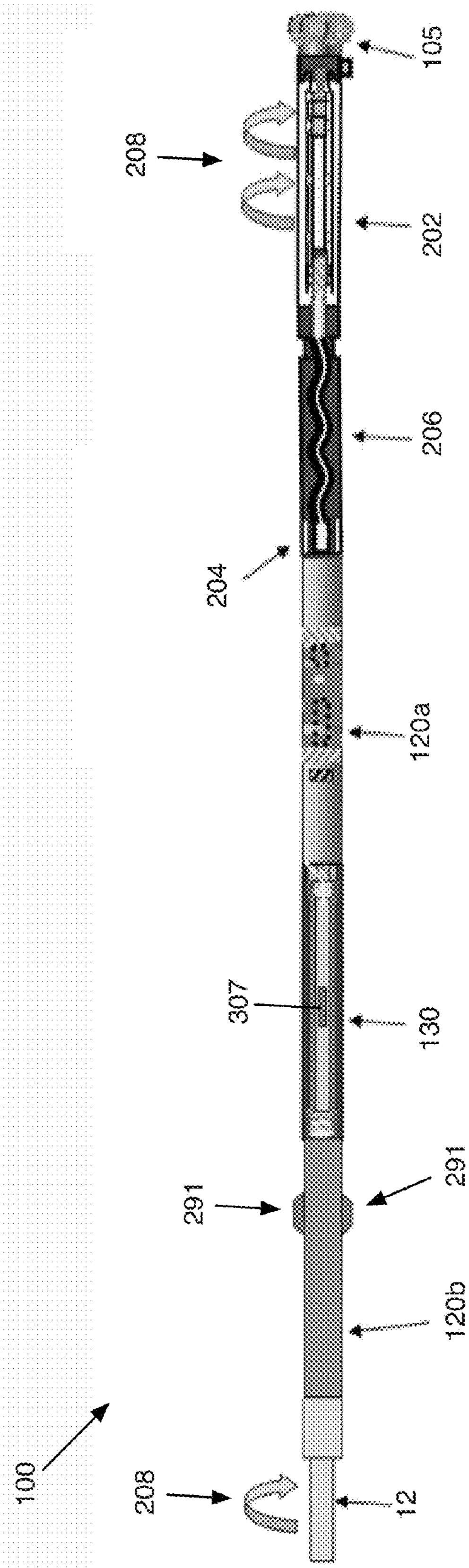

FIG. 20

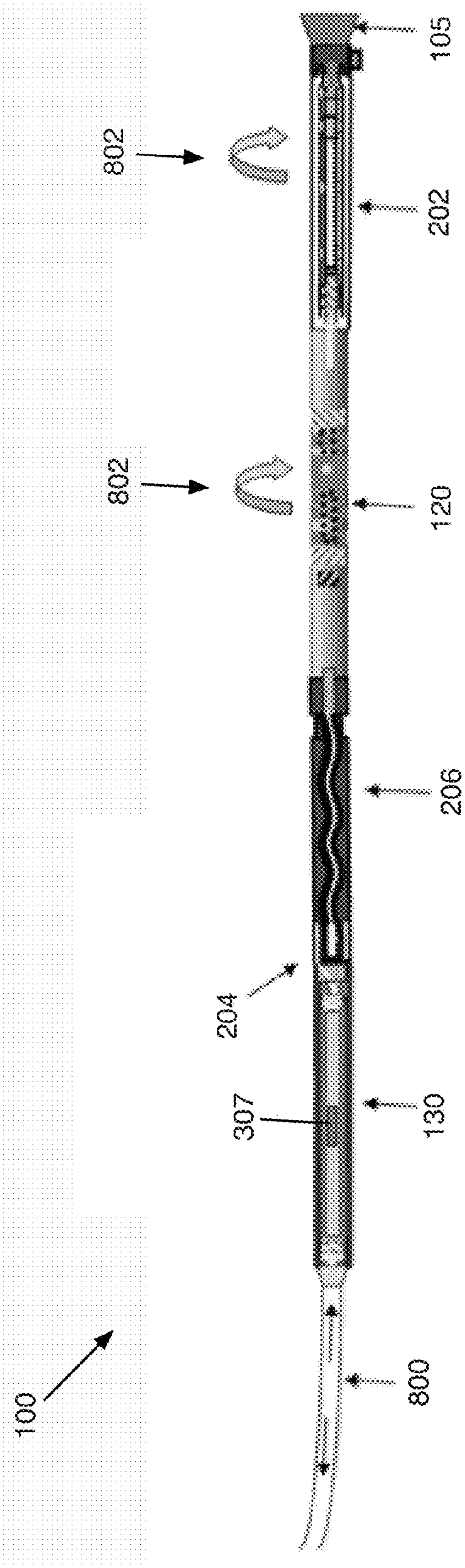

FIG. 21

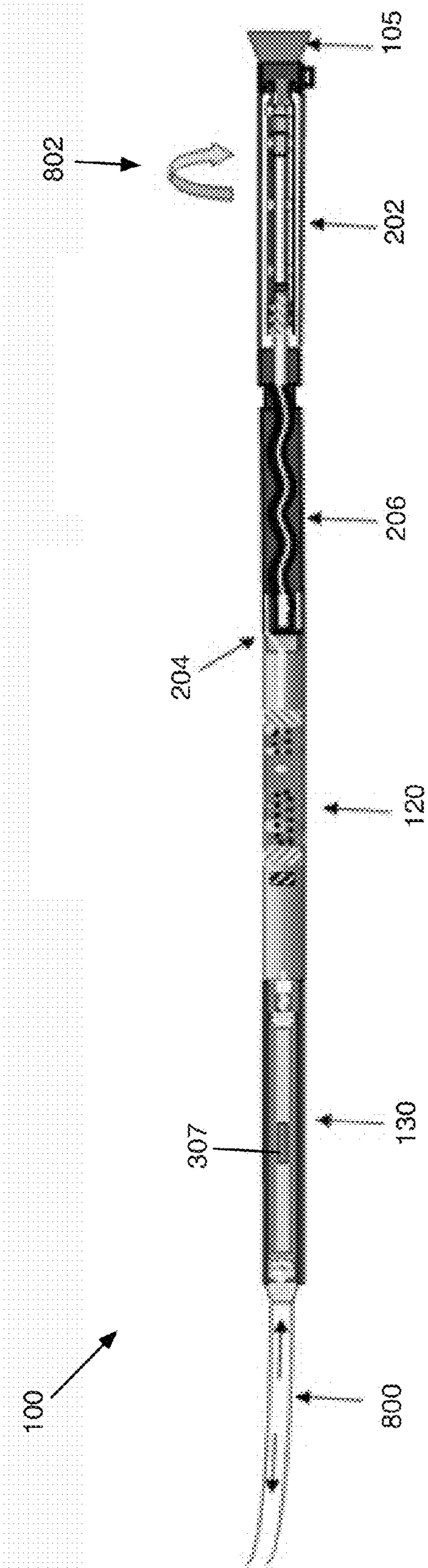

FIG. 22

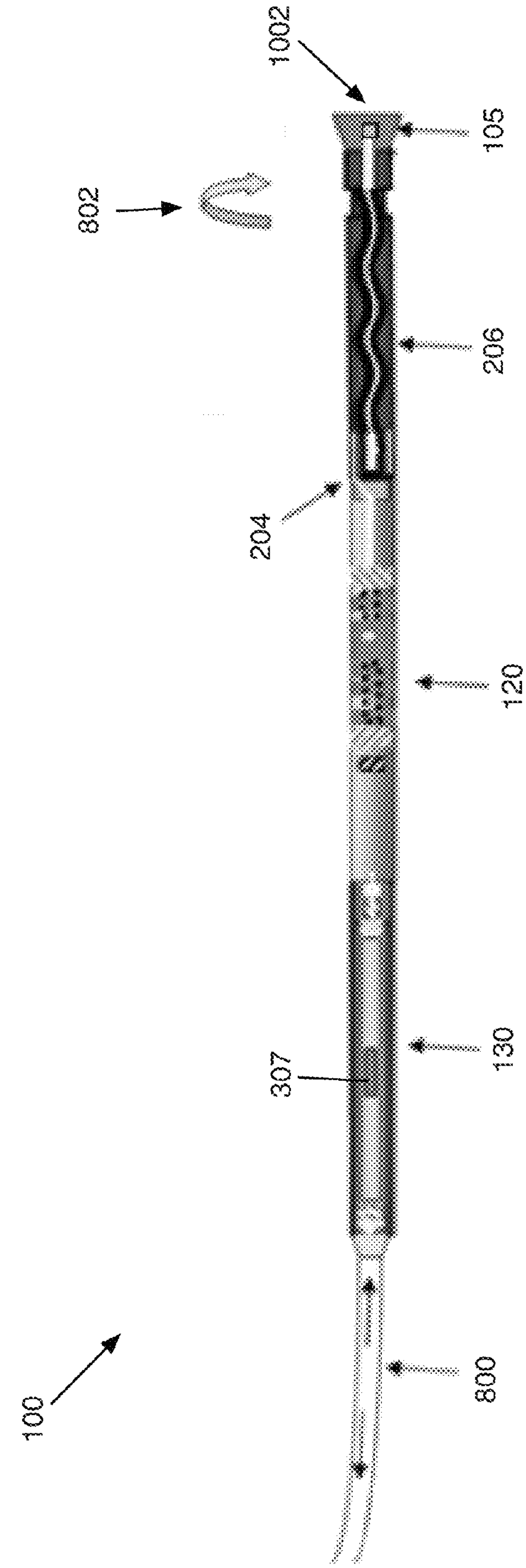

FIG. 23

DRILLING BOTTOM HOLE ASSEMBLY HAVING WIRELESS POWER AND DATA CONNECTION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of and priority to U.S. Provisional Patent Application Ser. No. 61/704,620, entitled "Drilling Bore Hole Assembly With A Wireless Power and Data Connection," and filed on Sep. 24, 2012, U.S. Provisional Patent Application Ser. No. 61/704,805, entitled "System And Method for Wireless Power And Data Transmission In A Mud Motor," and filed on Sep. 24, 2012, and U.S. Provisional Patent Application Ser. No. 61/704,758, entitled "Positive Displacement Motor Rotary Steerable System And Apparatus," and filed on Sep. 24, 2012, the disclosures of which are hereby incorporated by reference in their entireties.

DESCRIPTION OF THE RELATED ART

In drilling operations, such as directional applications, bottom hole assemblies (BHAs) have become increasingly sophisticated with various high performance elements. For example, BHAs may include rotary steerable systems (RSS), formation evaluation (FE) measurements, direction and inclination (D&I) measurements with high data rate mud pulse telemetry, and power generation systems from measuring-while-drilling (MWD) and logging-while-drilling (LWD) tools.

Drilling motors are increasingly used in conjunction with RSS and MWD/LWD BHAs, which creates various challenges for distributing power and data within the BHA components while maintaining optimal placement of the MWD system and the mud pulse telemetry within the BHA, as well as other measurements (e.g., FE, D&I, etc.) and functionalities in the BHA.

Furthermore, due to the high cost of deployment of the drilling operation, it is becoming increasingly desirable to optimize drilling performance. A methodology to optimize drilling performance is to measure downhole drilling conditions, and provide this information to the driller for adjusting various parameters, such as, weight on bit, drill pipe revolutions per minute, accelerations, stick and slip conditions, etc. Typically, this information is acquired in different locations of the BHA and recorded for surface analysis once the BHA is pulled out of the hole. A standard configuration for drilling optimization or directional drilling is to place a drilling mud motor between the drilling bit and the MWD. In this case, however, the transmission of power and data communications to the drill bit is technically challenging and costly because it has to cross a rotational joint in the mud motor.

Accordingly, there is a need in the art for improved BHA configurations for enabling power and data connectivity between components of the BHA.

SUMMARY OF THE DISCLOSURE

Various embodiments of system and methods are disclosed for providing wireless power and data communications in a bottom hole assembly. One such method includes coupling a measuring-while-drilling (MWD) module to a drill string. A wireless power and data connection is located above a drilling motor in the drill string for providing power and data between the MWD module and the drilling motor. A rotary steerable system (RSS) is coupled to the drilling motor for receiving power from and communicating with the MWD module via the wireless power and data connection.

Another embodiment is a bottom hole assembly (BHA) configured for use in a drill string of a wellsite drilling system. The BHA includes a measuring-while-drilling (MWD) module, a wireless power and data connection, and a rotary steerable system (RSS). The MWD module is configured for coupling to a drill string, and includes a power generation component and a direction and inclination (D&I) survey package. The wireless power and data connection is disposed above a drilling motor in the drill string for providing power and data connectivity between the MWD module and a drilling motor. The RSS is coupled to the drilling motor for receiving power from and communicating with the MWD module via the wireless power and data connection and the drilling motor.

This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

In the Figures, like reference numerals refer to like parts throughout the various views unless otherwise indicated. For reference numerals with letter character designations such as "**102**A" or "**102**B", the letter character designations may differentiate two like parts or elements present in the same figure. Letter character designations for reference numerals may be omitted when it is intended that a reference numeral to encompass all parts having the same reference numeral in all figures.

FIG. **1**A is a diagram of a system for enabling wireless power and data transfer between components in a drilling operation;

FIG. **1**B is a diagram of a wellsite drilling system that forms part of the system illustrated in FIG. **1**A;

FIG. **2** is a schematic drawing depicting a primary or transmitting circuit and a secondary or receiving circuit.

FIG. **3** is a schematic drawing depicting a primary or transmitting circuit and a secondary or receiving circuit with transformers having turn ratios N_S:1 and N_L:1 that may used to match impedances.

FIG. **4** is a schematic drawing depicting an alternative circuit to that which is depicted in FIG. **3** and having parallel capacitors that are used to resonate the coils' self-inductances.

FIGS. **5**A-**5**B illustrate an embodiment of a receiving coil inside a transmitting coil.

FIGS. **6**-**7** are graphs illustrating the variation in k versus axial displacement of the receiving coil when x=0 is small and the transverse displacement when z=0 produces very small changes in k of given embodiments, respectively.

FIGS. **8**-**9** are graphs illustrating that power efficiency may also be calculated for displacements from the center in the z direction and in the x direction, respectively, of given embodiments.

FIG. **10** is a graph illustrating that the sensitivity of the power efficiency to frequency drifts may be relatively small in some embodiments.

FIG. **11** is a graph illustrating that drifts in the components values of some embodiments do not have a large effect on the power efficiency of the embodiment.

FIG. **12** depicts a particular embodiment configured to convert input DC power to a high frequency AC signal, f_0, via a DC/AC convertor.

FIG. **13** depicts a particular embodiment configured to pass AC power through the coils.

FIG. **14** depicts a particular embodiment that includes additional secondary coils configured to transmit and receive data.

FIG. **15** is a diagram of an embodiment of a bottom hole assembly configuration for enabling wireless power and data transfer between components in the bottom hole assembly.

FIG. **16** is a diagram illustrating the MWD module and the wireless power and data connection of the bottom hole assembly of FIG. **15**.

FIG. **17** is a diagram illustrating another embodiment of a bottom hole assembly configuration that includes a LWD module for enabling wireless power and data transfer between components in the bottom hole assembly.

FIG. **18** is a diagram illustrating a further embodiment of a bottom hole assembly configuration that includes a LWD module.

FIG. **19** is a diagram illustrating a further embodiment of a bottom hole assembly configuration that includes a LWD module.

FIG. **20** is a diagram illustrating a further embodiment of a bottom hole assembly configuration that includes a LWD module.

FIG. **21** is a diagram illustrating another embodiment of a bottom hole assembly configuration for enabling wireless power and data transfer to a LWD module and rotary steerable system.

FIG. **22** is a diagram illustrating another embodiment of a bottom hole assembly configuration with an alternative position for LWD module.

FIG. **23** is a diagram illustrating another embodiment of a bottom hole assembly configuration that includes an embedded sensor in the drill bit for providing real-time measurements to the MWD module.

DETAILED DESCRIPTION

Various embodiments of systems and methods are disclosed for providing power and/or data communications in a drilling assembly. Referring initially to FIG. **1**A, this figure is a diagram of a system **102** for enabling wireless power and data transfer between components in a drilling operation. The system **102** includes a controller module **101** that is part of a controller **106**. The system **102** also includes a drilling system **104**, which has a logging and control module **95**, a bottom hole assembly ("BHA") **100**, and wireless power and data connections **204**. The controller **106** further includes a display **147** for conveying alerts **110**A and status information **115**A that are produced by an alerts module **110**B and a status module **115**B. The controller **102** may communicate with the drilling system **104** via a communications network **142**.

The controller **106** and the drilling system **104** may be coupled to the communications network **142** via communication links **103**. Many of the system elements illustrated in FIG. **1**A are coupled via communications links **103** to the communications network **142**.

The links **103** illustrated in FIG. **1**A may include wired or wireless couplings or links. Wireless links include, but are not limited to, radio-frequency ("RF") links, infrared links, acoustic links, and other wireless mediums. The communications network **142** may include a wide area network ("WAN"), a local area network ("LAN"), the Internet, a Public Switched Telephony Network ("PSTN"), a paging network, or a combination thereof. The communications network **142** may be established by broadcast RF transceiver towers (not illustrated). However, one of ordinary skill in the art recognizes that other types of communication devices besides broadcast RF transceiver towers are included within the scope of this disclosure for establishing the communications network **142**.

The drilling system **104** and controller **106** of the system **102** may have RF antennas so that each element may establish wireless communication links **103** with the communications network **142** via RF transceiver towers (not illustrated). Alternatively, the controller **106** and drilling system **104** of the system **102** may be directly coupled to the communications network **142** with a wired connection. The controller **106** in some instances may communicate directly with the drilling system **104** as indicated by dashed line **99** or the controller **106** may communicate indirectly with the drilling system **104** using the communications network **142**.

The controller module **101** may include software or hardware (or both). The controller module **101** may generate the alerts **110**A that may be rendered on the display **147**. The alerts **110**A may be visual in nature but they may also include audible alerts as understood by one of ordinary skill in the art.

The display **147** may include a computer screen or other visual device. The display **147** may be part of a separate stand-alone portable computing device that is coupled to the logging and control module **95** of the drilling system **104**. The logging and control module **95** may include hardware or software (or both) for direct control of a bottom hole assembly **100** as understood by one of ordinary skill in the art.

FIG. **1**B illustrates a wellsite drilling system **104** that forms part of the system **102** illustrated in FIG. **1**A. The wellsite can be onshore or offshore. In this system **104**, a borehole **11** is formed in subsurface formations by rotary drilling in a manner that is known to one of ordinary skill in the art. Embodiments of the system **104** can also use directional drilling, as will be described hereinafter. The drilling system **104** includes the logging and control module **95** as discussed above in connection with FIG. **1**A.

A drill string **12** is suspended within the borehole **11** and has a bottom hole assembly ("BHA") **100** which includes a drill bit **105** at its lower end. The surface system includes platform and derrick assembly **10** positioned over the borehole **11**, the assembly **10** including a rotary table **16**, kelly **17**, hook **18** and rotary swivel **19**. The drill string **12** is rotated by the rotary table **16**, energized by means not shown, which engages the kelly **17** at the upper end of the drill string. The drill string **12** is suspended from a hook **18**, attached to a traveling block (also not shown), through the kelly **17** and a rotary swivel **19** which permits rotation of the drill string **12** relative to the hook **18**. As is known to one of ordinary skill in the art, a top drive system could alternatively be used instead of the kelly **17** and rotary table **16** to rotate the drill string **12** from the surface. The drill string **12** may be assembled from a plurality of segments **125** of pipe and/or collars threadedly joined end to end.

In the embodiment of FIG. **1**B, the surface system further includes drilling fluid or mud **26** stored in a pit **27** formed at the well site. A pump **29** delivers the drilling fluid **26** to the interior of the drill string **12** via a port in the swivel **19**, causing the drilling fluid to flow downwardly through the drill string **12** as indicated by the directional arrow **8**. The drilling fluid exits the drill string **12** via ports in the drill bit **105**, and then circulates upwardly through the annulus region between the outside of the drill string and the wall of the borehole, as indicated by the directional arrows **9**. In this system as understood by one of ordinary skill in the art, the drilling fluid **26** lubricates the drill bit **105** and carries formation cuttings up to the surface as it is returned to the pit **27** for cleaning and recirculation.

The bottom hole assembly **100** of the illustrated embodiment may include a logging-while-drilling (LWD) module **120**, a measuring-while-drilling (MWD) module **130**, a rotary-steerable system and motor **150**, and drill bit **105**.

The LWD module **120** is housed in a special type of drill collar, as is known to one of ordinary skill in the art, and can contain one or a plurality of known types of logging tools. It will also be understood that more than one LWD **120** and/or MWD module **130** can be employed, e.g. as represented at **120**A. (References, throughout, to a module at the position of **120**A can alternatively mean a module at the position of **120**B as well.) The LWD module **120** includes capabilities for measuring, processing, and storing information, as well as for communicating with the surface equipment. In the present embodiment, the LWD module **120** includes a directional resistivity measuring device.

The MWD module **130** is also housed in a special type of drill collar, as is known to one of ordinary skill in the art, and can contain one or more devices for measuring characteristics of the drill string **12** and drill bit **105**. The MWD module **130** may further includes an apparatus (not shown) for generating electrical power to the downhole system **100**.

This apparatus may typically include a mud turbine generator powered by the flow of the drilling fluid **26**, it being understood by one of ordinary skill in the art that other power and/or battery systems may be employed. In the embodiment, the MWD module **130** includes one or more of the following types of measuring devices: a weight-on-bit measuring device, a torque measuring device, a vibration measuring device, a shock measuring device, a stick slip measuring device, a direction measuring device, and an inclination measuring device.

The foregoing examples of wireline and drill string conveyance of a well logging instrument are not to be construed as a limitation on the types of conveyance that may be used for the well logging instrument. Any other conveyance known to one of ordinary skill in the art may be used, including without limitation, slickline (solid wire cable), coiled tubing, well tractor and production tubing.

FIGS. **2**-**14** illustrate various embodiments for implementing the wireless power and data connection **204**. As described below in more detail, the wireless power and data connection **204** generally includes a wireless, tuned-inductive coupler mechanism for passing both power and data communications to downhole components in a bottom hole assembly. It should be appreciated that the wireless power and data connection **204** may be incorporated in various types and configurations of drilling assemblies.

FIG. **2** is a schematic drawing depicting a primary or transmitting circuit **210** and a secondary or receiving circuit **220**. In this description, the time dependence is assumed to be $\exp(j\omega t)$ where $\omega=2\pi f$ and f is the frequency in Hertz. Returning to the FIG. **2** illustration, the transmitting coil is represented as an inductance L_1 and the receiving coil as L_2. In the primary circuit **210**, a voltage generator with constant output voltage V_S and source resistance R_S drives a current I_1 through a tuning capacitor C_1 and primary coil having self-inductance L_1 and series resistance R_1. The secondary circuit **220** has self-inductance L_2 and series resistance R_2. The resistances, R_1 and R_2, may be due to the coils' wires, to losses in the coils magnetic cores (if present), and to conductive materials or mediums surrounding the coils. The Emf (electromotive force) generated in the receiving coil is V_2, which drives current I_2 through the load resistance R_L and tuning capacitor C_2. The mutual inductance between the two coils is M, and the coupling coefficient k is defined as:

$$k=M/\sqrt{L_1L_2} \tag{1}$$

While a conventional inductive coupler has $k\approx1$, weakly coupled coils may have a value for k less than 1 such as, for example, less than or equal to about 0.9. To compensate for weak coupling, the primary and secondary coils in the various embodiments are resonated at the same frequency. The resonance frequency is calculated as:

$$\omega_0 = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}} \tag{2}$$

At resonance, the reactance due to L_1 is cancelled by the reactance due to C_1. Similarly, the reactance due to L_2 is cancelled by the reactance due to C_2. Efficient power transfer may occur at the resonance frequency, $f_0=\omega_0/2\pi$. In addition, both coils may be associated with high quality factors, defined as:

$$Q_1 = \frac{\omega L_1}{R_1} \text{ and } Q_2 = \frac{\omega L_2}{R_2}. \tag{3}$$

The quality factors, Q, may be greater than or equal to about 10 and in some embodiments greater than or equal to about 100. As is understood by one of ordinary skill in the art, the quality factor of a coil is a dimensionless parameter that characterizes the coil's bandwidth relative to its center frequency and, as such, a higher Q value may thus indicate a lower rate of energy loss as compared to coils with lower Q values.

If the coils are loosely coupled such that $k<1$, then efficient power transfer may be achieved provided the figure of merit, U, is larger than one such as, for example, greater than or equal to about 3:

$$U=k\sqrt{Q_1Q_2}>>1. \tag{4}$$

The primary and secondary circuits are coupled together via:

$$V_1=j\omega L_1I_1+j\omega MI_2 \text{ and } V_2=j\omega L_2I_2+j\omega MI_1, \tag{5}$$

where V_1 is the voltage across the transmitting coil. Note that the current is defined as clockwise in the primary circuit and counterclockwise in the secondary circuit. The power delivered to the load resistance is:

$$P_L = \frac{1}{2}R_L|I_2|^2, \tag{6}$$

while the maximum theoretical power output from the fixed voltage source V_S into a load is:

$$P_{MAX} = \frac{|V_S|^2}{8R_S}. \tag{7}$$

The power efficiency is defined as the power delivered to the load divided by the maximum possible power output from the source,

$$\eta \equiv \frac{P_L}{P_{MAX}}. \tag{8}$$

In order to optimize the power efficiency, η, the source resistance may be matched to the impedance of the rest of the circuitry. Referring to FIG. **2**, Z_1 is the impedance looking from the source toward the load and is given by:

$$Z_1 = R_1 - j/(\omega C_1) + j\omega L_1 + \frac{\omega^2 M^2}{R_2 + R_L + j\omega L_2 - j/(\omega C_2)} \tag{9}$$

When $\omega=\omega_0$, Z_1 is purely resistive and may equal R_S for maximum efficiency.

$$Z_1 = R_1 + \frac{\omega^2 M^2}{R_2 + R_L} \equiv R_S. \tag{10}$$

Similarly, the impedance seen by the load looking back toward the source is

$$Z_2 = R_2 - j/(\omega C_2) + j\omega L_2 + \frac{\omega^2 M^2}{R_1 + R_S + j\omega L_1 - j/(\omega C_1)} \tag{11}$$

When $\omega=\omega_0$, Z_2 is purely resistive and R_L should equal Z_2 for maximum efficiency

$$Z_2 = R_2 + \frac{\omega^2 M^2}{R_1 + R_S} \equiv R_L. \tag{12}$$

The power delivered to the load is then:

$$P_L = \frac{1}{2}\frac{R_L\omega_0^2 M^2 |V_S|^2}{[(R_S + R_1)(R_2 + R_L) + \omega_0^2 M^2]^2}, \tag{13}$$

and the power efficiency is the power delivered to the load divided by the maximum possible power output,

$$\eta \equiv \frac{P_L}{P_{MAX}} = \frac{4R_S R_L \omega_0^2 M^2}{[(R_S + R_1)(R_2 + R_L) + \omega_0^2 M^2]^2}. \tag{14}$$

The optimum values for R_L and R_L may be obtained by simultaneously solving

$$R_S = R_1 + \frac{\omega^2 M^2}{R_2 + R_L} \text{ and } R_L = R_2 + \frac{\omega^2 M^2}{R_1 + R_S}, \tag{15}$$

with the result that:

$$R_S=R_1\sqrt{1+k^2Q_1Q_2} \text{ and } R_L=R_2\sqrt{1+k^2Q_1Q_2}. \tag{16}$$

If the source and load resistances do not satisfy equations (16), then it is envisioned that standard methods may be used to transform the impedances. For example, as shown in the FIG. **3** illustration, transformers with turn ratios N_S:1 and N_L:1 may be used to match impedances as per equations (16). Alternatively, the circuit illustrated in FIG. **4** may be used. In such an embodiment in FIG. **4**, parallel capacitors are used to resonate the coils' self-inductances according to equation (2). As before, Z_1 is defined as the impedance seen by the source looking toward the load, while Z_2 is defined as the impedance seen by the load looking toward the source. In addition, there are two matching impedances, Z_S and Z_T which may be used to cancel any reactance that would otherwise be seen by the source or load. Hence Z_1 and Z_2 are purely resistive with the proper choices of Z_S and Z_T. Notably, the source resistance R_S may equal Z_1, and the load resistance R_L may equal Z_2. The procedures for optimizing efficiency with series capacitance or with parallel capacitance may be the same, and both approaches may provide high efficiencies.

Turning now to FIGS. **5**A and **5**B, a cross sectional view of two coils **232**, **234** is illustrated in FIG. **5**A and a side view of the two coils **232**, **234** is illustrated in FIG. **5**B. In these two figures, a receiving coil **232** inside a transmitting coil **234** of a particular embodiment **230** is depicted. The receiving coil **232** includes a ferrite rod core **235** that, in some embodiments, may be about 12.5 mm (about 0.49 inch) in diameter and about 96 mm (about 3.78 inches) long with about thirty-two turns of wire **237**. Notably, although specific dimensions and/or quantities of various components may be offered in this description, it will be understood by one of ordinary skill in the art that the embodiments are not limited to the specific dimensions and/or quantities described herein.

Returning to FIG. **5**, the transmitting coil **234** may include an insulating housing **236**, about twenty-five turns of wire **239**, and an outer shell of ferrite **238**. The wall thickness of the ferrite shell **238** in the FIG. **5** embodiment may be about 1.3 mm (about 0.05 inch). In certain embodiments, the overall size of the transmitting coil **234** may be about 90 mm (about 3.54 inch) in diameter by about 150 mm (about 5.90 inches) long. The receiving coil **232** may reside inside the transmitting coil **234**, which is annular.

The receiving coil **232** may be free to move in the axial (z) direction or in the transverse direction (x) with respect to the transmitting coil **234**. In addition, the receiving coil **232** may be able to rotate on axis with respect to the transmitting coil **234**. The region between the two coils **232**, **234** may be filled with air, fresh water, salt water, oil, natural gas, drilling fluid (known as "mud"), or any other liquid or gas. The transmitting coil **234** may also be mounted inside a metal tube, with minimal affect on the power efficiency because the magnetic flux may be captured by, and returned through, the ferrite shell **238** of the transmitting coil **234**.

The operating frequency for these coils **232**, **234** may vary according to the particular embodiment, but, for the FIG. **5** example 230, a resonant frequency f=100 kHz may be assumed. At this frequency, the transmitting coil **234** properties are: $L_1=6.76\cdot10^{-5}$ Henries and $R_1=0.053$ ohms, and the receiving coil **232** properties are $L_2=7.55\cdot10^{-5}$ Henries and $R_2=0.040$ ohms. The tuning capacitors are $C_1=3.75\cdot10^{-8}$ Farads and $C_2=3.36\cdot10^{-8}$ Farads. Notably, the coupling coefficient k value depends on the position of the receiving coil **232** inside the transmitting coil **234**. The receiving coil **232** is centered when x=0 and z=0 and there is k=0.64.

The variation in k versus axial displacement of the receiving coil **232** when x=0 may be relatively small, as illustrated by the graph **250** in FIG. **6**. The transverse displacement when z=0 may produce very small changes in k, as illustrated by the graph **252** in FIG. **7**. The receiving coil **232** may rotate about the z-axis without affecting k because the coils are azimuthally symmetric. According to equations (16), an optimum value for the source resistance may be R_S=32 ohms, and for the load resistance may be R_L=24 ohms when the receiving coil **232** is centered at x=0 and z=0. The power efficiency may thus be η=99.5%.

The power efficiency may also be calculated for displacements from the center in the z direction in mm (as illustrated by the graph **254** in FIG. **8**) and in the x direction in mm (as illustrated by the graph **256** in FIG. **9**). It is envisioned that the efficiency may be greater than about 99% for axial displacements up to about 20.0 mm (about 0.79 inch) in certain embodiments, and greater than about 95% for axial displacements up to about 35.0 mm (about 1.38 inches). It is further envisioned that the efficiency may be greater than 98% for transverse displacements up to 20.0 mm (about 0.79 inch) in some embodiments. Hence, the position of the receiving coil **232** inside the transmitting coil **234** may vary in some embodiments without reducing the ability of the two coils **232**, **234** to efficiently transfer power.

Referring now to FIG. **10**, it can be seen in the illustrative graph **258** where the Y-axis denotes efficiency in percentage and the X-axis denotes frequency in Hz that the sensitivity of the power efficiency to frequency drifts may be relatively small. A ±10% variation in frequency may produce minor effects, while the coil parameters may be held fixed. The power efficiency at 90,000 Hz is better than about 95%, and the power efficiency at 110,000 Hz is still greater than about 99%. Similarly, drifts in the component values may not have a large effect on the power efficiency. For example, both tuning capacitors C_1 and C_2 are allowed to increase by about 10% and by about 20% as illustrated in the graph **260** of FIG. **11**. Notably, the other parameters are held fixed, except for the coupling coefficient k. The impact of the power efficiency is negligible. As such, the system described herein would be understood by one of ordinary skill in the art to be robust.

It is also envisioned that power may be transmitted from the inner coil to the outer coil of particular embodiments, interchanging the roles of transmitter and receiver. It is envisioned that the same power efficiency would be realized in both cases.

Referring to FIG. **12**, an electronic configuration **262** is illustrated for converting input DC power to a high frequency AC signal, f_0, via a DC/AC convertor. The transmitter circuit in the configuration **262** excites the transmitting coil at resonant frequency f_0. The receiving circuit drives an AC/DC convertor, which provides DC power output for subsequent electronics. This system **262** is appropriate for efficient passing DC power across the coils.

Turning to FIG. **13**, AC power can be passed through the coils. Input AC power at frequency f_1 is converted to resonant frequency f_0 by a frequency convertor. Normally this would be a step up convertor with $f_0 >> f_1$. The receiver circuit outputs power at frequency f_0, which is converted back to AC power at frequency f_1. Alternatively, as one of ordinary skill in the art recognizes, the FIG. **13** embodiment **264** could be modified to accept DC power in and produce AC power out, and vice versa.

In lieu of, or in addition to, passing power, data signals may be transferred from one coil to the other in certain embodiments by a variety of means. In the above example, power is transferred using an about 100.0 kHz oscillating magnetic field. It is envisioned that this oscillating signal may also be used as a carrier frequency with amplitude modulation, phase modulation, or frequency modulation used to transfer data from the transmitting coil to the receiving coil. Such would provide a one-way data transfer.

An alternative embodiment includes additional secondary coils to transmit and receive data in parallel with any power transmissions occurring between the other coils described above, as illustrated in FIG. **14**. Such an arrangement may provide two-way data communication in some embodiments. The secondary data coils **266**, **268** may be associated with relatively low power efficiencies of less than about 10%. It is envisioned that in some embodiments the data transfer may be accomplished with a good signal to noise ratio, for example, about 6.0 dB or better. The secondary data coils **266**, **268** may have fewer turns than the power transmitting 234 and receiving coils **232**.

The secondary data coils **266**, **268** may be orthogonal to the power coils **232**, **234**, as illustrated in FIG. **14**. For example, the magnetic flux from the power transmitting coils **232**, **234** may be orthogonal to a first data coil **266**, so that it does not induce a signal in the first data coil **266**. A second data coil **268** may be wrapped as shown in FIG. **14** such that magnetic flux from the power transmitters does not pass through it, but magnetic flux from first data coil **266** does. Notably, the configuration depicted in FIG. **14** is offered for illustrative purposes only and is not meant to suggest that it is the only configuration that may reduce or eliminate the possibility that a signal will be induced in one or more of the data coils by the magnetic flux of the power transmitting coils. Other data coil configurations that may minimize the magnetic flux from the power transmitter exciting the data coils will occur to those with ordinary skill in the art.

Moreover, it is envisioned that the data coils **266**, **268** may be wound on a non-magnetic dielectric material in some embodiments. Using a magnetic core for the data coils **266**, **268** might result in the data coils' cores being saturated by the strong magnetic fields used for power transmission. Also, the data coils **266**, **268** may be configured to operate at a substantially different frequency than the power transmission frequency. For example, if the power is transmitted at about 100.0 kHz in a certain embodiment, then the data may be transmitted at a frequency of about 1.0 MHz or higher. In such an embodiment, high pass filters on the data coils **266**, **268** may prevent the about 100.0 kHz signal from corrupting the data signal. In still other embodiments, the data coils **266**, **268** may simply be located away from the power coils **232**, **234** to minimize any interference from the power transmission. It is further envisioned that some embodiments may use any combination of these methods to mitigate or eliminate adverse effects on the data coils **266**, **268** from the power transmission of the power coils **232**, **234**.

Having described the structure and operation of various embodiments of the wireless power and data connection **204** with reference to FIGS. **2-14**, various embodiments of configurations of a BHA **100** incorporating a wireless power and data connection will be described. The BHA configurations illustrate different embodiments for arranging various components within the BHA **100**. These and other BHA configurations may provide wireless power and data transfer to components above and/or below a downhole drilling motor **206** and, thereby, advantageously enable real-time measurement and control of various drilling conditions for optimizing drilling performance and/or reducing drilling costs.

In the embodiment of FIG. **15**, the BHA **100** includes a MWD module **130** connected to drill string **12**. The MWD module **130** includes a system including, for example, power component(s), telemetry component(s), and a directional & inclination (D&I) survey package **307**. A wireless power and data connection **204** may be attached to the downhole end of the MWD module **130**. This wireless power and data connection **204** is described above in connection with FIGS. **2-14**.

The wireless power and/or data connection **204** may be used to replace the physical single pin connection typically found in conventional drilling and measurement (D&M)

tools. As described above with reference to FIGS. **2-14**, the wireless power and/or data connection **204** includes a wireless, tuned-inductive coupler mechanism for passing both power and data communications to downhole components of the BHA **100**. It should be appreciated that separate coils may be used for power and communication transmissions as described above and illustrated in FIG. **14**.

Below the drill string **12**, the MWD module **130** is connected to the drilling motor **206**, which is in turn connected to the RSS **202**. RSS **202** and motor **206** are one embodiment of the rotary-steerable system and motor **150** illustrated in FIG. 1B. A drill bit **105** is attached to the downhole end of the RSS **202**. Power and/or data pass through the wireless connection **204** between the MWD module **130** and the drilling motor **206**.

It should be appreciated that the placement of the MWD module **130** and the D&I survey package above the drilling motor **206** provides certain desirable features, including allowing surveys to be taken while pumping. This configuration may avoid the need for a battery in the MWD module **130** for performing stationary surveys with the drilling pumps disabled.

If the MWD module **130** is located below the drilling motor **206**, the pumps must be disabled to stop rotation of the D&I survey package. Furthermore, turbine power is not available when pumps are off, so a battery must be used to power the D&I survey package along with logic using other parts of the system to detect when pumps are off. In the BHA configuration illustrated in FIG. **2**, the placement of the mud pulse telemetry in the MWD module **130** above the drilling motor **206** also avoids attenuation of data signals due to the pulses passing through the drilling motor **206**, which can be particularly problematic at higher data rates.

Referring again to FIG. **15**, the wireless power and/or data connection **204** allows relative rotational motion (reference numeral **208**) between the MWD module **130** (which is coupled to the external housing of the drilling motor **206**) and the rotor of the drilling motor **206** (which is connected to the RSS **202** and the drill bit **105**), allowing power and data transfer throughout the entire BHA **100**. The RSS **202** may rotate at a higher RPM than the drill string **12** because it is below the drilling motor **206**.

FIG. **16** illustrates in more detail the wireless power and data connection **204** disposed between the MWD module **130** and the drilling motor **206**. Power and data connections exit the downhole end of a modulator and turbine power system and are coupled to a stationary coil **306** of the wireless power and data connection **204**, which may be located in the external housing of the drilling motor **206**. Power and/or data are transmitted between the stationary coil **306** and a rotating coil **304** via tuned-inductive methods described in detail above in connection with FIGS. **5A-5B**. Wiring is coupled to the rotating coil **304** and passes through an interior sealed channel in the center of the rotor **302** of the drilling motor **206**.

At the downhole or bottom end of the rotor, the wire terminates at a connection **308** to the RSS **202**. In an embodiment, the connection **308** may include a threaded rotary shouldered joint and a sealed electrical connector that mechanically and electrically couples the rotating mechanism of the drilling motor **206** to the RSS **202**.

Various additional BHA embodiments and configurations are illustrated in FIGS. **17-20**. In the embodiment of FIG. **17**, the LWD module **120** is located below the drilling motor **206** in the BHA **100**. The LWD module **120** is disposed between the drilling motor **206** and the RSS **202**. The LWD module **120** is connected to the drilling motor **206** via the wired rotor.

In the embodiments of FIGS. **18-20**, the LWD module **120** is disposed above rather than below the drilling motor **206**. In this BHA configuration, the LWD module is adjacent the MWD module **130** and, therefore, will not be rotated by the drilling motor **206**. It should be appreciated that this BHA configuration may provide certain advantages with respect to operational conditions, such as, for example, shock, vibrations, stick/slip, measurement proximity to the drill bit **105**, measurement physics, etc.

One of ordinary skill in the art will appreciate that these BHA configurations are not the only possible configurations, but merely presented to illustrate the flexibility of component placement when using a drilling motor **206** with wireless power and data capability. In FIG. **18**, the LWD module **120** is disposed between the MWD module **130** and the drilling motor **206**. In the configuration illustrated in FIG. **19**, the location of the LWD module **120** and the MWD module **130** are reversed, such that the MWD module **130** is located closer to the drilling motor **206**. The LWD module **120** is disposed above, and connects to, the MWD module **130**.

The embodiment illustrated in FIG. **20** includes two LWD modules: a primary LWD module **120***a* and a secondary LWD module **120***b*. The primary LWD module **102***a* may be disposed between the drilling motor **206** and the MWD module **130**, and the secondary LWD module **102***b* may be disposed above the MWD module **130**. The multi-LWD configuration may advantageously provide for a plurality of different types and combinations of measurements.

In an embodiment, the primary LWD module **102***a* may enable measurements, such as, for example, the resistivity of the surrounding formation and/or fluids. The secondary LWD module **102***b* may be configured for borehole diameter, density, and neutron porosity measurements. In this regard, the LWD module **102***b* may include one or more pads **291** disposed on the outer housing. The pads **291** may include mounted sensors for taking appropriate measurements.

It should be further appreciated that additional BHA configurations may enable measurements at the drilling bit **105** when using the drilling motor **206**. In operation, the drill bit **105** is driven by the drilling motor **206** to form the borehole while simultaneously permitting measurements and communications with the LWD module **120**, the MWD module **130**, or other components of the system **102** (FIG. **1**).

The drill bit **105** may be rotated by the drilling motor **206** or by another suitable driving device. The drill bit **105** and other BHA components may have a variety of sensors and signal transmission systems to provide an operator with real-time data and/or other data useful in both drilling the borehole and/or steering the BHA **100** along a variety of desired trajectories through a reservoir.

A drilling motor **206** with a wireless power and data connection **204** enables the BHA **100** to pass power and data communication from an uphole component to a downhole component and vice versa. FIGS. **21-23** illustrate additional BHA configurations that provide further flexibility in the placement of the MWD module **130** and the LWD **120**, and which enable measurements at the drill bit **105** when using the drilling motor **206**. These embodiments may be implemented in various drilling contexts, including coupling to a coiled tube **800**, and may incorporate full rotation of the rotor of the drilling motor **206** and enable the power generation to be positioned on the uphole side of the drilling motor **206** while sensors and/or the LWD tools may be placed on the downhole side of the drilling motor **206**.

FIG. **21** illustrates a D&M BHA **100** that includes a drilling motor **206** with a wireless power and data connection **204**, a MWD module **130**, a LWD module **120**, and a RSS **202**. The

MWD module **130** is connected to the drilling motor **206**, which is in turn connected to an assembly having LWD module **120**, RSS **202**, and drill bit **105**. Power and/or data pass through the wireless connection **204** between the modulator/turbine power system and the drilling motor **206**. The wireless connection **204** allows relative motion (reference numeral **802**) between the MWD module **130** (which is coupled to the external housing of the drilling motor **206**) and the rotor of the drilling motor **206** (which is wired and coupled to the RSS/LWD/drill bit assembly), allowing power and data transfer throughout the entire BHA.

In this regard, the MWD module **130** may remain stationary, which may be advantageous for certain types of measurements. The LWD module **120**, however, may be located below the drilling motor **206** (i.e., the rotating side), which may be advantageous to, for example, capture images by scanning around the borehole while the LWD module **120** rotates.

If added rotation of the LWD module **120** from the drilling motor **206** is not desired, an alternative arrangement of the BHA components may be employed, as illustrated in FIG. **22**. In this embodiment, the LWD module **120** may be located to the non-rotating side of the drilling motor **206** and connected to a downhole end of the MWD module **130**.

A further embodiment, as illustrated in FIG. **23**, may include a direct connection of the drill bit **105** to the drilling motor **206**. In this BHA configuration, the drill bit **105** may include a sensor **1002** for providing real-time measurements to the MWD module **130** that may be transmitted across the wireless connection **204** as described in detail above.

Although only a few embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the embodiments without materially departing from this invention. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims.

In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures. It is the express intention of the applicant not to invoke 35 U.S.C. §112, sixth paragraph for any limitations of any of the claims herein, except for those in which the claim expressly uses the words 'means for' together with an associated function.

What is claimed is:

1. A method for providing wireless power and data communications in a bottom hole assembly for use in a drill string, the method comprising:

coupling a measuring-while-drilling (MWD) module to a drill string;

locating a wireless power and data connection above a drilling motor in the drilling string, the wireless power and data connection for providing power and data between the MWD module and the drilling motor; and

coupling a rotary steerable system (RSS) to the drilling motor for receiving power from and communicating with the MWD module via the wireless power and data connection;

electrically coupling first and second coils in the wireless power and data connection with a coupling coefficient, k, wherein, $k=M/\sqrt{L_1L_2}\leq 0.9$, M is a mutual inductance between the first and second coils, L_1 is a first self-inductance of the first coil, and L_2 is a second self-inductance of the second coil; and

resonantly tuning the first coil at a first frequency, f_1, with a first capacitance, C_1, and the second coil at a second frequency, f_2, with a second capacitance, C_2, wherein f_1 is approximately equal to f_2,

$$f_1 = \frac{1}{2\pi\sqrt{L_1C_1}} \text{ and } f_2 = \frac{1}{2\pi\sqrt{L_2C_2}};$$

wherein the first and second coils have a figure of merit, U, wherein $U=k\sqrt{Q_1Q_2}\geq 3$,

$$Q_1 = \frac{2\pi f_1 L_1}{R_1},\ Q_2 = \frac{2\pi f_2 L_2}{R_2},$$

Q_1 and Q_2 comprise respective quality factors associated with the first and second coils, and R_1 and R_2 comprise respective resistances of the first and second coils.

2. The method of claim **1**, wherein the MWD module comprises a power generation component and a direction and inclination (D&I) survey package.

3. The method of claim **1**, wherein the wireless power and data connection comprises a first coil located within a second coil.

4. The method of claim **3**, wherein the first and second coils comprise cylindrical wire coils.

5. The method of claim **3**, wherein the first coil comprises an inner coil comprising a wire wrapped on a core of material having a relatively high magnetic permeability.

6. The method of claim **3**, further comprising:

approximately matching a source impedance of the first coil, R_s, with a load impedance of the second coil, R_1, wherein $R_S\approx R_1\sqrt{1+k^2Q_1Q_2}$.

7. The method of claim **3**, further comprising:

approximately matching a load impedance of the second coil, R_1, with a source impedance of the first coil, R_S, wherein $R_L\approx R_2\sqrt{1+k^2Q_1Q_2}$.

8. The method of claim **3**, further comprising:

transmitting power between the first and second coils.

9. The method of claim **3**, further comprising:

transmitting data between the first and second coils.

10. The method of claim **9**, wherein the transmitting data between the first and second coils comprises modulating one of an amplitude, a phase, and a frequency of a current.

11. A bottom hole assembly (BHA) configured for use in a drill string of a wellsite drilling system, the BHA comprising:

a measuring-while-drilling (MWD) module configured for coupling to a drill string, the MWD module comprising a power generation component and a direction and inclination (D&I) survey package;

a wireless power and data connection disposed above a drilling motor in the drilling string, and for providing power and data connectivity between the MWD module and the drilling motor; and

a rotary steerable system (RSS) coupled to the drilling motor for receiving power from and communicating with the MWD module via the wireless power and data connection and the drilling motor;

wherein the wireless power and data connection comprises a pair of inductively coupled coils wherein:

the pair of coils comprise a first coil located within a second coil and the first and second coils are coupled with a coupling coefficient, k, wherein, $k=M/\sqrt{L_1 L_2} \leq 0.9$, M is a mutual inductance between the first and second coils, L_1 is a first self-inductance of the first coil, and L_2 is a second self-inductance of the second coil;

the first coil is resonantly tuned at a first frequency, f_1, with a first capacitance, C_1, and the second coil at a second frequency, f_2, and the second coil is resonantly tuned with a second capacitance, C_2, wherein f_1 is approximately equal to f_2,

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}} \text{ and } f_2 = \frac{1}{2\pi\sqrt{L_2 C_2}};$$

and

the first and second coils have a figure of merit, U, wherein $U=k\sqrt{Q_1 Q_2} \geq 3$,

$$Q_1 = \frac{2\pi f_1 L_1}{R_1},\ Q_2 = \frac{2\pi f_2 L_2}{R_2},$$

Q_1 and Q_2 comprise respective quality factors associated with the first and second coils, and R_1 and R_2 comprise respective resistances of the first and second coils.

12. The BHA of claim **11**, wherein the first coil comprises an inner coil comprising a wire wrapped on a core of material having a relatively high magnetic permeability.

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